METHODS AND SYSTEMS FOR CALIBRATION AND COMPENSATION OF ACCELEROMETERS WITH BIAS INSTABILITY

BACKGROUND OF THE INVENTION

[0001] This invention relates generally to calibration and compensation of accelerometers, and more specifically, to calibration and compensation of accelerometers with bias instability.

[0002] Most accelerometers incorporate one of two types of sensing elements. One sensing element type is a piezo-resistive sensor in which acceleration causes a resistance change in the sensing element itself. The resistance change thereby causes a change a time constant upon which accelerometer output is based. The other sensing element type is a capacitive sensor. In such a sensor, capacitance change is caused by a change in the spacing between capacitive elements due to acceleration. The capacitance change therefore causes a change in a time constant upon which accelerometer output is based.

[0003] Certain known accelerometers demonstrate bias instability. The bias instability is typically one or more of temperature cycle hysteresis and high gravitational force bias accumulation, which is sometimes referred to as anelastic bias response. These instabilities are of concern, and may prevent use of certain accelerometers, in particular applications, for example, guidance products. However, with proper calibration and compensation, the accelerometers can be used effectively in some applications, particularly in applications where bias accumulation occurs during testing but not in the actual application.

BRIEF DESCRIPTION OF THE INVENTION

[0004] In one aspect, a method for determining compensation coefficients for accelerometers is provided. The method comprises estimating bias accumulation from measured accelerometer outputs, determining a corrected

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accelerometer output, and determining the compensation coefficients using the corrected accelerometer output.

[0005] In another aspect, a method for compensating for bias instabilities in accelerometers is provided. The method comprises removing temperature cycle hysteresis through temperature cycling, limiting durations of high acceleration load dwell times, and determining a corrected accelerometer output to compensate for bias accumulated during high acceleration load dwell times.

[0006] In still another aspect, a method of removing bias accumulation from an accelerometer measured output, the output being measured at a center point of time t_c, of a high acceleration load interval of more than 1g is provided. The method comprises estimating bias accumulation at the center point of time, t_c, according to $\frac{1}{2}(a(t_2)-a(t_1))$, where $a(t_1)$ is measured accelerometer output for a 1g load at a time prior to a beginning of the high acceleration load interval, and $a(t_2)$ is measured accelerometer output for a 1g load at a time after an end of the high acceleration load interval and correcting accelerometer output according to $a_c = a(t_c) - \frac{1}{2}(a(t_2)-a(t_1))$, where $a(t_c)$ is measured accelerometer output at the center point of the high acceleration load interval.

[0007] In yet another aspect, a system configured to determine compensation coefficients for an accelerometer is provided. The system comprises a computer comprising a processor and a memory, a rate table comprising a chamber, and a rate table controller connected to the computer and configured to run acceleration load profiles on the rate table, the acceleration load profiles stored in the memory of the computer. The system further comprises a temperature controller connected to the computer and configured to run temperature profiles in the chamber, the temperature profiles also stored in the memory of the computer. The system also comprises a device configured to measure output of accelerometers, the computer configured to receive and store output data from the device. The computer is also configured to estimate bias accumulation from measured accelerometer outputs, determine corrected accelerometer

outputs, and determine compensation coefficients using the corrected accelerometer outputs.

[0008] In a further aspect, a computer for removing bias accumulation from accelerometer measured outputs is provided, the outputs being measured at a center point of time of a high acceleration load interval of more than 1g. The computer is configured to estimate bias accumulation at the center point of time, t_c, according to $\frac{1}{2}(a(t_2)-a(t_1))$, where $a(t_1)$ is measured accelerometer output for a 1g load at time prior to a beginning of the high acceleration load interval, and $a(t_2)$ is measured accelerometer output for a 1g load at a time after an end of the high acceleration load interval and correct accelerometer output according to $a_c = a(t_c)-\frac{1}{2}(a(t_2)-a(t_1))$, where $a(t_c)$ is measured accelerometer output at the center point of time.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] Figure 1 is a block diagram of a high speed rate table system.

[0010] Figure 2 is a flowchart of a method for compensation of bias instability in accelerometers.

[0011] Figure 3 is a flowchart of a compensation coefficient determination method.

[0012] Figure 4 is a graph illustrating bias instability due to temperature cycling.

[0013] Figure 5 is a graph illustrating bias accumulation for an accelerometer being operated at a high acceleration load.

[0014] Figure 6 is a graph illustrating decay of accumulated bias.

[0015] Figure 7 is a graph illustrating a load and temperature profile for a typical accelerometer test.

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[0016] Figure 8 is a graph illustrating the bias accumulation that accumulated during the high acceleration load periods of the accelerometer test decaying during the low acceleration load intervals.

[0017] Figure 9 is a graph illustrating an accelerometer output during a high acceleration load interval.

[0018] Figure 10 is a graph illustrating bias differences due to bias accumulation between accelerometer output at a beginning and at an end of a high acceleration loading interval.

[0019] Figure 11 is a graph illustrating accelerometer output and a second derivative of accelerometer output for during a high acceleration load interval.

DETAILED DESCRIPTION OF THE INVENTION

[0020] Figure 1 is a block diagram of a high speed rate table system 10. System 10 is, in one embodiment, configured to perform temperature and acceleration testing of accelerometers 12 by application of temperature cycles and acceleration load cycles. Acceleration load cycles are implemented using a high speed rate table 14. Rate table 14 includes a chamber 16 in which accelerometers 12 are mounted. A temperature inside chamber 16 is controlled by a temperature controller 18, allowing temperature cycling. Acceleration within chamber 16 are controlled by a rate table controller 20. Temperature and acceleration cycling programs are stored in a memory (not shown) of computer control 22. Running such programs causes temperature controller 18 and rate table controller 20 to cycle temperatures and acceleration forces at table 14. Computer control 22 further receives and stores accelerometer output data from an accelerometer output measuring device 24.

[0021] In one embodiment, system 10 is configured to implement methods to remove bias instability, for example, bias accumulation. Bias accumulation can affect accuracy of compensation coefficients calculated for accelerometers. Compensation coefficients typically are calculated for individual accelerometers and stored in a memory of a device, for example, a guidance product, which processes accelerometer output as part of an overall control program.

[0022] Figure 2 is a flow chart illustrating process steps for a method 30 for removal of bias instabilities. Method 30 could be performed, for example, by system 10 (shown in Figure 1). Method 30 includes a determination of corrected accelerometer output to remove bias accumulation. Temperature cycle hysteresis is removed 32 through temperature cycling of the accelerometer. Bias accumulation is minimized 34 by limiting high acceleration load dwell times. A corrected accelerometer output is determined 36 to account for bias accumulation that accrues during high acceleration testing.

[0023] Figure 3 is a flowchart illustrating process steps for a method 40 of determining compensation coefficients for accelerometers. Method 40 could be performed, for example, by system 10 (shown in Figure 1). Bias accumulation is estimated 42 from measured accelerometer outputs allowing a corrected accelerometer output to be calculated 44. Compensation coefficients are calculated 46 using the corrected accelerometer output.

[0024] Figure 4 is a graph 60 which illustrates bias instability due to temperature cycling. Bias instability due to temperature cycling, referred to herein as temperature cycle hysteresis is known, as are methods for reducing the amount of instability (hysteresis) through temperature cycling. Graph 60 includes a cumulative bias shift portion 62 and a change in bias shift portion 64, for three sample accelerometers. The vertical axis of portion 62 and portion 64 represent a 100Hz integrated accelerometer output in feet per second (ft/sec), and a 1g load corresponds to 32.15 ft/sec^2 × 0.01 sec, or 0.32 ft/sec. The hysteresis is measured, and graphed, as an accelerometer output change in ft/sec. Referring to cumulative portion 62, cumulative temperature hysteresis, is substantially exponential until about the 60th temperature cycle, at which point the cumulative change in accelerometer output approaches an asymptote. Referring to portion 64, it is noted that accelerometer output can change as much as 0.1 ft/sec over the first 40 or so temperature cycles. After about 60 cycles, changes in accelerometer bias due to temperature cycling reaches an acceptable level of change for most accelerometer applications.

[0025] Standard temperature cycling methodologies are used, including temperature ranging, with temperature ramps in degrees centigrade/minute, and dwell

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times at certain test temperatures. In one embodiment, standard temperature cycling is part of a method for reducing bias instability in accelerometers.

[0026] Figure 5 is a graph 70 illustrating bias accumulation 72 for an example accelerometer which is being operated at a high acceleration load of 50g and a temperature 74 of 33 degrees centigrade. As shown on graph 70, under high acceleration loads, and especially at higher temperatures, accelerometers "accumulate" bias. Specifically, the accelerometer under test had operated for five minutes at 1g prior to the application of the 50g load. As shown on graph 70, when a high acceleration load is applied which lasts approximately five to ten minutes, bias accumulates approximately linearly. When the load is applied for a longer duration (not shown), for example, 20 minutes, accumulated bias 72 approaches an asymptote.

[0027] Figure 6 is a graph 100 illustrating decay of accumulated bias 102. Graph 100 is a continuation in time of graph 70 (shown in Figure 5). The decay shown on graph 100 is after reduction of a 50g load that had been applied for ten minutes to a 1g load. The accumulated bias 102 decays approximately exponentially with a time constant on the order of two minutes. The size of the decay is approximately equal to the bias accumulated during the high load, e.g. 50g load, application. For one particular accelerometer and test, about 0.04 ft/sec of bias accumulated during the high load interval. For reference, a 1g accelerometer output prior to the high load interval 104 is also shown.

[0028] Based on such accumulation and decay, an approximate rate equation for bias accumulation effect, b, is given by $\dot{b} = c_1(T)l - c_2(T)b$, where c_i are temperature (T) dependent constants for a particular accelerometer, l is the load applied, and $c_2(T)b$ is a decay term.

[0029] In one embodiment, accelerometers are compensated only after temperature cycling, described above with respect to Figure 4, reduces temperature cycle hysteresis to acceptable levels. Accelerometer testing is also implemented to reduce bias accumulation. In a particular embodiment, in order to minimize bias accumulation, high acceleration load dwell times are limited to a five second duration. Other relatively short high acceleration load dwell times are also contemplated. Load

ramps, a time period when g load on an accelerometer increases from a first level to a second level, in one embodiment, occurs over an approximately 20 second time period. Other load ramping time periods are also contemplated. In the embodiment described, the load ramps occur at both the beginning of the load dwell time, that is from a 1g load to a 50g load, and at the end of the load dwell time, from 50g to 1g. In the embodiment, prior to subsequent high acceleration loads, accelerometers were operated with ±1g loads for 5-10 minutes to allow the accumulation to decay. Although the example described herein describes a high acceleration load as 50g and a low acceleration load as 1g, it will be appreciated that the methods described herein are applicable for other acceleration load values. Any load value where bias accumulation is an acceptable or negligible value can be considered a low acceleration load value and any load value where bias accumulation is unacceptable can be considered a high acceleration load value.

[0030] Figure 7 is a graph 200 of a load 202 and temperature 204 profile for a typical accelerometer test performed at 70 degrees centigrade. Additional accelerometer tests are performed at one or more different temperatures.

[0031] Referring to graph 200, a first 30 to 45 minutes of the accelerometer test are used to ramp to the approximate temperature level, e.g. 70 degrees centigrade. As shown in the profile illustrated by graph 200, there is included approximately five minutes of bias accumulation decay time (i.e. low acceleration time) between applications of high acceleration loads. At temperatures at or above 45 degrees centigrade, some accelerometers require ten or more minutes of low acceleration load time between application of high acceleration loads to recover from bias accumulation. Figure 8 is a graph 250 which shows the bias accumulation accumulated during the high acceleration load periods of the accelerometer test decaying during the low acceleration intervals. Graph 250 is the same accelerometer test as shown in graph 200, but the accelerometer output axis is charted using a finer accelerometer output scale, thereby allowing the decay in bias accumulation to be seen.

[0032] Analysis of the data from accelerometer tests is used to account for bias accumulation. Since some flight profiles of the equipment into which the accelerometers are incorporated is of such short duration, e.g. a missile flight time of

four seconds, bias accumulation is negligible during flight. Therefore, bias accumulation which occurs during accelerometer testing needs to be removed from test data before compensation coefficients are determined. Bias accumulation is removed from test data by making three assumptions. First, an assumption is made that bias accumulation is negligible at the beginning of each high acceleration testing interval. The assumption is valid since the 5-10 minutes of low acceleration load time between high acceleration intervals allows previously accumulated bias to decay.

[0033] Second, it is assumed that the decay term $c_2(T)b$ is negligible during each high acceleration loading interval since the duration of the interval is a relatively short time. Such an approximation is reasonable since $|c_1(T)l| \rangle\rangle |c_2(T)b|$ throughout most of the testing interval, where $c_1(T)l$ is the rate of bias accumulation during high acceleration load testing.

[0034] A third assumption is that temperature does not change significantly during the short term of the high acceleration loading interval. The 30-45 minute temperature ramping and 1g load dwell at the beginning of calibration runs allows this approximation to be made.

[0035] Figure 9 is a graph 300 which illustrates an accelerometer output during a high acceleration interval, for example, one of the high acceleration loading intervals shown in Figure 8. The accelerometer output indicates symmetry and an approximately five second stable region which occurs surrounding a center point in time of the high acceleration interval. In one embodiment, compensation coefficients are determined based upon accelerometer output $a(t)$ at a center t_c of the stable region. For example, and in one known testing scenario, in the middle of the high acceleration interval, an acceleration table rate is stable for approximately 5 seconds, as shown on graph 300. Referring to graph 300, accelerometer output, a, is charted as a function of time, t. Accelerometer output at a center point, t_c, of the stable region in each of the high acceleration intervals is used in determination of compensation coefficients. However, and as described above, bias accumulates during the acceleration ramp (application of the high acceleration load) and continues to accumulate during the time period the acceleration table rate is stable. In order to use the accelerometer output at

the center point, $a(t_c)$, to determine compensation coefficients for an accelerometer, the accumulated bias at time t_c should be removed.

[0036] The symmetry of the high acceleration loading interval, allows an approximation of the bias accumulation at the middle of the interval. Figure 10 is a graph 350 which indicates differences between a 1g load accelerometer output at a time prior to a beginning and at a time after an end of a high acceleration loading interval of an accelerometer test. The differences in accelerometer output between the time prior to the beginning and the time after the end of the high acceleration load allows an approximation of the bias accumulated during the high acceleration loading interval, in particular, an approximation of the bias accumulation at the middle of the interval. Bias accumulation at the center of the stable region is considered to be one half of the bias accumulated by the end of the high acceleration interval. To approximate bias accumulated at the center of the stable region, one half of the difference of the 1g outputs measured at the time after the end of the high acceleration interval and at the time prior to the beginning of the high acceleration interval is used. The time after the end of the high acceleration interval and the time prior to the beginning of the high acceleration interval are sometimes referred to herein as high acceleration interval endpoints. The approximated bias accumulation is then subtracted from the accelerometer output at the high acceleration load center point before determination of compensation coefficients.

[0037] Figure 11 is a graph 400 of accelerometer output $a(t)$ 402 and a second derivative 404 of accelerometer output $a''(t)$ which are used, in one embodiment, to determine bias accumulation at the center of the stable region of the high acceleration interval. Location of the high acceleration interval endpoints and center of the stable high acceleration load region are determined using accelerometer output data. In one embodiment, the second derivative of the accelerometer output is used to determine the high acceleration interval endpoints because 1g output from uncompensated accelerometers varies by accelerometer and by temperature. Graph 400 illustrates a sharp definition of the high acceleration loading interval provided by the second derivative 404. The 1g time and output $a(t)$ and the second derivative $a''(t)$ of the output at the time prior to the beginning and the time after the end of the high acceleration

interval are shown as $(a(t_1), a''(t_1))$ and $(a(t_2), a''(t_2))$, respectively. Once the high acceleration interval endpoints t_1 and t_2 are found, a calibration data point is determined and corrected for bias accumulation according to $t_c = \frac{1}{2}(t_1 + t_2)$ and $a_c = a(t_c) - \frac{1}{2}(a(t_2) - a(t_1))$. Other methods for determining high acceleration interval endpoints are also contemplated, for example, first derivatives of accelerometer output.

[0038] Other error sources are taken into account when determining compensation coefficients for accelerometers, for example, effects on a radius arm of an acceleration rate table due to thermal expansion and centrifugal forces of the acceleration rate table. Positive g and negative g radius arms as a function of temperature for one known acceleration rate table are described by

$r_p = 4.466 + 0.0001T + 2.13\times10^{-11}\dot{\theta}^2$ inches and

$r_n = 1.552 + 0.00005T + 1.22\times10^{-11}\dot{\theta}^2$ inches, where T is in degrees Celsius and θ is in rotational degrees per second. Temperature and rotational rate dependent radius arms for other acceleration rate tables may be determined. For a particular temperature, rotation rate, and orientation, the change to the stationary room temperature radius can be determined using the corrections in the positive and negative g radius arm equations above.

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[0039] A simulated change in velocity over 0.01 second for a particular rotation rate, temperature, and orientation, which is used in determining accelerometer compensation coefficients is given by $dv_{load} = \frac{r_{p/n}}{1200}\left(\frac{2\pi\dot{\theta}}{360}\right)^2 \quad (ft/\sec)$.

[0040] However, the load at $r_{p/n}$ may be different than the load at the sense element because of variation in the location of the sense element within the accelerometer package. Radius error is asymmetric with respect to direction, and is determined as part of a compensation model. Second order effects due to the location of the sense element are negligible.

[0041] In one embodiment, calibration of accelerometer output includes calculating a load during testing, which is calculated as

$\left(\frac{r_{p/n} \pm dr_{error}}{r_{p/n}}\right) dv_{load} = \left(w_0 + w_1 T + dv_{out}\left(w_2 + w_3 T + w_4 T^2 + w_5 T^3\right) + w_6 dv_{out}^2\right)$, where dv_{load} is the change in velocity for the applied load and approximate radius arm, $r_{p/n}$, dv_{out} is accelerometer output, T is temperature, dr_{error} is an accelerometer sensing element radial error to be determined, and w_i are calibration coefficients to be determined. To determine dr_{error} and the w_i coefficients, the accelerometers are tested at multiple temperatures and multiple loads, as described above, thereby producing multiple outputs. The results of these multiple tests are then used to solve for dr_{error} and w_i using specific dv_{load}, dv_{out}, and T for each accelerometer test performed, using known mathematical methods. $r_{p/n}$ is an approximate radius arm for positive g (p) and negative g (n) orientations. By substituting the corrected accelerometer output, a_c, as determined using the methods described above for the term dv_{out} ,correct values for dr_{error} and w_i can be determined.

[0042] To accurately compensate for temperatures and loads during operational use in an application, for example, a guidance product, the product is configured with the compensation model $dv_{load} = \left(w_0 + w_1 T + dv_{out}\left(w_2 + w_3 T + w_4 T^2 + w_5 T^3\right) + w_6 dv_{out}^2\right)$, using the values calculated for w_i , and therefore the product is able to minimize errors at any operational temperature and output. In the application, bias accumulation is not removed from dv_{out}.

[0043] While the invention has been described in terms of various specific embodiments, those skilled in the art will recognize that the invention can be practiced with modification within the spirit and scope of the claims.